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ICST/IAT Automation Project Experimental Investigation of Drill-Bit Wear

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This is an interim report. The work described constitutes the first stage of a more complex effort, results and conclusions are not necessarily those that would be included in a summary report.

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ABSTRACT

The development of an experimental instrumentation system for a small drill press is described. The parameters measured are spindle speed, vertical spindle displacement, vertical spindle load, drilling torque, and drilling time. Several test fixtures were instrumented and used in drilling experiments. These experiments were conducted to examine the relationship between variations in the measured parameters and drill performance, more specifically to drill wear. Experimental data show a 10-percent increase in drilling time from the first hole to the last for a single set of 500 holes drilled in cold-rolled steel at a nominally constant load, although the drilling time began to decrease slightly after hole 300. Changes in drilling torque were also detected during the test runs, and in similar runs with a brass workpiece. It is suggested that with respect to the anomalous results in steel under the unlubricated, constant-force conditions employed, the cutting surfaces of the drill bit were in a sense being renewed as microflakes of material departed to reveal fresh, sharp unburnished sites.

Key words: cutting force; drill bit; drill press; dynamic; force; load; machine tool; measurement; on-line; tool wear; torque; transducer.

1. INTRODUCTION

Metal removal is a multi-billion dollar business in the United States; nearly all manufacturing operations require metal removal at some stage of manufacture. Cutting tools wear as various machining operations proceed and must be replaced or sharpened. The dulling or wearing of machine tool bits and cutters may often not take place in a predictable fashion: one tool may last three or four times as long as a similar tool in a similar application. In production, tools are generally replaced after a given number of operations determined on the basis of experience in performing the given operation or a similar operation; this empirical approach usually has a conservative bias to avoid the risk of damaged workpieces and catastrophically failed tools, and thus may result in tool

replacement before it is necessary. The most efficient utilization of a tool would probably involve use to incipient failure or degradation of surface finish. In addition, it is often desirable to perform a machining operation at as high a speed as possible, consistent with finish requirements and the need not to overheat the cutting edges of the tool. These considerations suggest that it would be desirable to have an on-line means of monitoring the condition of the cutter or tool bit being used. The availability of condition information as input for a digital computer (microprocessor?) could then permit near-optimum machining conditions to be achieved.

The "Study on Automation" prepared by the NBS Visiting Committee in 1975 recommended an NBS-wide program on automation technology having as one major emphasis a concentration on developing the basis for the measurement of performance and calibration parameters for dynamic sensors having fast response, and the development of standards for such sensors.

Late in FY 1976, the Office of Developmental Automation and Control Technology (DACT) of the Institute for Computer Sciences and Technology, and the Electronic Technology Division of the Institute for Applied Technology, began a cooperative task supported by the Director's Reserve Fund. One task element was to instrument a small drill press as a test bed and to conduct a variety of experiments with it in order to determine preliminary performance measures for this machine tool. As part of this task, the suitability of selected sensors was to be evaluated, particularly in regard to measurements of tool wear. The intent is that this preliminary work lead to further experimental work, in turn resulting in the development of specific calibration and evaluation methods for selected sensors. The use of the drill press as a readily available and at the same time representative machine tool was based on DACT-industry contacts and a tool-wear sensing survey [1].*

A second task element was to conduct a limited, English-language literature survey to gather information on the types of sensors used and measurements made in support of worldwide efforts in machine-tool automation. The resulting review and bibliography are published separately as NBSIR 78-1424 [2].

2. EXPERIMENTAL INVESTIGATION OF DRILL-BIT WEAR

2.1 Instrumentation of Drill Press

2.1.1 <u>Selection of Characteristics to be Measured</u> - A number of drill-press characteristics that are considered to relate to tool wear are available to be measured. Parameters that have been measured include:

(1) force of drill bit against workpiece,

(2) torque of drill bit with respect to workpiece,

(3) downward displacement of drill bit during cutting process,

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*Figures in brackets indicate literature references in section 5.

(4) drill spindle speed,

(5) time required for a given drilling operation;

(6) time-averaged drill-press motor current,

(7) amplitude and frequency of vibration of the workpiece or drill bit, and

(8) temperature of the drill bit at the cutting edges.

An *a priori* objective was to identify that parameter or combination of parameters most sensitive to or indicative of tool wear or condition. Selection of parameters for initial investigation was subject to considerations of measurement ease and cost. Since it was not clear on the basis of the literature reviewed which characteristics would prove the most sensitive, it was decided to concentrate on the set of mechanical parameters: force, torque, displacement, and drilling time, with spindle speed as an incidental measurement. Vibration frequency and amplitude were not measured *per se* because the variations in force between the drill bit and the workpiece yield the same information. Non-mechanical measurements were postponed as being more difficult of interpretation as well as accomplishment; temperature in particular is regarded as an important parameter in considerations of wear mechanisms.

It is important to note that both static and dynamic measurements provide useful information.

<u>2.1.2 Description of Drill Press</u> - The drill press used in the drilling experiments is a 38-cm (15-in) floor model with a 1.3-cm (0.5-in) drill-bit capacity. Spindle speed is selected by means of the conventional belt and stepped-pulley arrangement to provide nominal no-load speeds of 725, 1300, 2500, and 4650 rpm.

<u>2.1.3 Drill-Press Modifications</u> - To provide a nominally constant feeding force, the drill press was modified by removing the hand lever which raises and lowers the spindle and replacing it with a large aluminum disk, or pulley, 46 cm in diameter and 1.3 cm thick. This pulley is mounted rigidly to the pinion shaft in the same plane as the hand lever, and is shown in figure 1 at F. A machined groove in the outer edge provides a guide for the drive rope. The rope transmits a constant force to the pulley and hence a constant force is developed between the drill bit and the workpiece. For different experiments, the force is adjusted by removing or adding weights to the pan attached to one end of the rope, as shown in the figure at D. The rope is fastened to the pulley groove at a point that becomes the top of the pulley with the spindle raised ready for drilling. The other end of the rope is led around the back side of the pulley and attached to the shaft of a low-speed, geared motor. This arrangement permits lowering of the spindle at a controlled rate until the workpiece is engaged in order to prevent excessive force and torque transients, which may be unrelated to the actual process of drilling. The rate of lowering is adjusted to be greater than the rate of penetration of the workpiece by the bit.

The modifications described provide a constant-load mode of operation. This mode was chosen for initial investigation as being simple to effect and easy to analyze. Another mode frequently used in machining is that of constant feed rate; it is intended that later investigations be extended to include this mode.

2.1.4 Measured Parameters

2.1.4.1 Spindle Speed - A 60-tooth steel gear is mounted on top of the drill-spindle pulley; a magnetic sensing coil mounted as shown in figure 2 generates a pulse each time a gear tooth is detected. Spindle speed is read directly in rpm with the sensing pulses as input for an electronic counter set to a counting interval of 1 s.

2.1.4.2 Spindle Displacement in Vertical Plane - The sensing coil of a linear-variable-differential transformer (LVDT) displacement transducer with a range of ± 2.5 cm and an output of ± 10 V dc from its associated signal-conditioning instrumentation is mounted concentric to the armature by means of a bracket attached to the head casting. For convenience, and to avoid the need for permanent modifications to drill-press components, the transducer armature is attached to a bracket mounted rigidly to the bottom of the vertical stop adjustment screw, as shown in figure 3. Thus, as the drill spindle moves up and down, the armature moves with it.

2.1.4.3 Force and Torque - In the case of the displacement and spindle-speed measurements, it is possible to locate instrumentation where it does not interfere with the drilling process. Envisioned instrumentation for load (force) and torque, however, has to be positioned close to, or concentric with, the drill bit. While for later work this instrumentation will have to be designed and located so that its interference with the drilling process is held to a minimum, the initial emphasis is on making measurements and not on the convenience or practicality of a test fixture.

In the course of this investigation, two different test fixtures incorporating force and torque sensors were built and used as described in the following paragraphs.

In the first test-fixture embodiment, an LVDT load cell with a range of 0 to 30 kgf is mounted on a base plate; this base plate is in turn mounted on the drill-press table so that the direction of motion of the load-cell armature is aligned with the axis of the drill bit. The exposed top of the armature is fitted with a machined cap that is slightly rounded on its top. A machined block has a shallow hole in its under surface sized to fit loosely over the cap and carries the jaws from a small machinist's vise on its upper surface. The vise assembly is free to move up and down and to rotate on the rounded cap as a bearing, but is constrained from moving in a lateral direction by brackets which engage slots machined in the sides of the block. This arrangement is clearly seen in the photograph of figure 4. The vise assembly is fitted with an arm that is spring-loaded to contact the armature of a second load cell mounted so that its armature motion is parallel to the drill-press table. This second load cell is similar to the first, but with a

measurement range of 0 to 9 kgf. In use, as the drill bit engages the workpiece held in the vise assembly, load (force) is measured by the load cell supporting the assembly, and torque is measured indirectly via the arm bearing against the second load cell. The spring-loading of the arm is intended to prevent chattering.

In a second design, the load cell is mounted between the two sides of a length of steel U-channel and preloaded to ensure that the cell always sees a downward force. The preload of about 10 to 20 percent of the full-scale range of the load cell is achieved by inserting shim stock between the top of the load-cell armature and the inside of the upper side of the channel. The bottom side of the channel is bolted to the drill-press table and positioned so that the drill-bit axis and load-cell axis are aligned. A result of this arrangement, shown in the photograph of figure 5, is that the effective range of the load cell is reduced.

A 1.3-cm diameter brass rod is threaded into the top surface of the channel; the axis of this rod is also aligned with the axis of the drill bit. A small vise equipped with a projecting arm is attached rigidly to the upper end of the brass rod. As with the first model, the level arm is loaded to contact the armature of a second load cell, mounted so that its armature motion is parallel to that of the drill-press table. The loading is accomplished by forcing the load cell against the lever arm; the brass rod thus serves as a torsion bar. The preload is usually set to about 10 to 20 percent of the load-cell range and is adjusted by inserting shim stock between the load cell armature and the arm. The two load cells used in model 2 are bonded strain-gage instruments with a range of 0 to 45 kgf. As the drill bit engages a workpiece held in the vise, the force is transmitted through the brass rod and through the cantilevered top side of the channel to be measured by the load cell. The torque is measured indirectly, as before. A strain gage is mounted on the brass rod at an angle of 45 deg to the rod axis as an additional means of checking the torque calculated from the load-cell data.

<u>2.1.4.4 Drill Penetration Time</u> - No specific instrumentation is required for measuring the time required to drill through a given workpiece. This time is determined by scale measurement of a signal trace from the load cell measuring downward force, as displayed on the screen of a storage oscilloscope. The times at which touch-down on the workpiece and breakthrough occur are readily determined from such a trace.

2.2 Test Procedure

<u>2.2.1 Drilling Considerations</u> - Starting with a new 1-cm diameter drill bit (high-speed type, as obtained from the NBS storeroom), a series of 500 successive holes was drilled in "1/4 hard brass" stock 1.3 cm thick. The nominal constant force applied by the drill bit to the workpiece was adjusted to be 260 kgf. The nominal drill spindle speed was 725 rpm. The nominal feed rate (intentionally not held constant) was 425 μm per revolution. These values were selected with guidance from tables in *Machinery's Handbook* [3]. This first experiment was followed by a similar

one in which 500 successive holes were drilled in 1.3-cm thick type 1015-1020 AISI steel. The nominal constant force applied by the drill bit to the workpiece in these tests was adjusted to be 620 kgf. The nominal drill spindle speed was again 725 rpm. The nominal feed rate (again intentionally not held constant) was 90 μm per revolution. Because drill wear was not expected to change rapidly, and to reduce the data-collection task, data were not taken for every hole drilled. The instrumentation was active during the drilling of 15 pairs of holes. These holes were 1 and 2, 10 and 11, 20 and 21, 40 and 41, 60 and 61, 80 and 81, 100 and 101, 150 and 151, 200 and 201, 250 and 251, 300 and 301, 350 and 351, 400 and 401, 450 and 451, and 499 and 500. It was intended that in the event that any measured parameter showed sudden change, the interval between instrumented pairs would be reduced accordingly. However, in neither experiment was any sudden change observed.

2.2.2 Load (Force) Measurements - In order to obtain both low- and high-frequency information, the instrumentation signals from the second hole in each measured pair were processed somewhat differently from those from the first hole.

As the first hole was being drilled, the output signal of the load cell measuring downward force was fed through a 5-Hz low-pass filter and then recorded on a storage oscilloscope (the resulting trace is shown in figures 6 and 7 for steel and brass, respectively). Neglecting vibration and friction effects, the load applied to the drill bit was constant. A 500-ms portion of the load-cell output signal was also captured by a transient recorder with 1024 eight-bit data points. The timing of this operation was intended to capture data just after the bit had fully engaged the workpiece. The output signal from the transient recorder was first fed through a 16-Hz low-pass filter and displayed on the oscilloscope, 16 Hz being chosen so that the 12-rps spindle frequency could be readily detected. The same output signal from the transient recorder was then fed through a 32-Hz low-pass filter and again displayed on an oscilloscope, 32 Hz being chosen so that the 2 times 12 rps flute frequency (the bit has two flutes) could be readily detected if present. Finally, the same signal from the transient recorder was fed into a frequency analyzer set to monitor frequencies from 0 to 200 Hz and the results photographed.

The second hole was then drilled, and again the output signal from the load cell recorded after passing through a 5-Hz low-pass filter; the data for consecutive drillings could thus be compared. With brass test pieces, the transient recorder was set to record a 10-ms portion of the load-cell output signal; the recorded signal was fed into the frequency analyzer set to monitor frequencies from 0 to 10 kHz. The 10-ms recording interval was used only for brass; for steel, a 50-ms recording interval was used and the frequency analyzer set to monitor frequencies from 0 to 2 kHz in an effort to improve the resolution of the test data.

2.2.3 Torque Measurements - The output signal from the load cell used to determine torque was processed in a manner analogous to that described in 2.2.2 for the signal representing downward force. In order to provide a

convenient means of comparing the timing of drilling events, as detected by the two load cells, load and torque traces are recorded on the same photograph.

2.2.4 Other Measurements - As described previously, drilling time was scaled directly from the photograph of the load-cell signal trace. A trace representing spindle displacement was also displayed on the oscilloscope (along with load and torque) and was used to monitor the drilling rate. The no-load spindle rotation frequency was displayed on a frequency meter and was used at the beginning and end of each test series as a check that the drill motor speed had not changed by more than 2 percent.

Table 1 is a summary of measurement conditions for the set of eight photographs obtained in the drill wear test for each pair of holes.

2.3 Test Results

2.3.1 Results with First Test Fixture - Load and torque information was provided by the first test fixture but was accompanied by considerable instability and vibration at the workpiece. Excessive play in the vise assembly holding the workpiece was caused primarily by efforts to reduce friction in the torque-measurement apparatus. Redesign of the vise did not appreciably reduce the vibration. Although a considerable number of tests were run, the data are regarded as invalid and are not presented here. The second test fixture was designed to eliminate or reduce the problems encountered with the first model and proved to be successful in this regard. All experimental data presented in this report were obtained with the second test fixture.

2.3.2 Results with Second Test Fixture - The test data are largely in the form of photographs of oscilloscope displays. As an example, see photograph A of figure 6, in which the top trace shows the output signal from the load (force) sensor as fed through a 5-Hz low-pass filter. The traces shown in figure 6 were obtained during the drilling of holes 1, 100, 200, 300, 400, and 500. Although a constant force was applied by the masses, this force was transmitted through the drill-press gearing so that the force between the drill bit and the workpiece varied from hole to hole because of friction. The total variation in downward force attributed to friction as determined from the 30 monitored holes in the 500-hole series in steel was estimated to be about ± 5 percent of the nominal value. This estimate refers to the near steady-state values of load and not to the vibration-induced a-c ripple superimposed on top of the steady-state load. Observation of this ripple is discussed later in this section.

The middle trace of photograph A of figure 6 represents the output signal from the torque load cell through a 5-Hz low-pass filter. As the drill bit first touches down on the workpiece, there is little torque because the tip of the bit constitutes a point contact; as the drill-bit flute area in contact with the workpiece increases, the torque increases similarly. The torque signal shows spikes in output at the beginning and the end of drilling with a plateau in between. The cause of the beginning spike is not known, but it, and some contribution to the spike at

the end of the drilling, may result from the fact that the surfaces of the workpiece are "... cold worked and therefore tougher than the undisturbed central zone" [3]. The greater part of the end spike is probably the result of the drill bit's breaking through the workpiece and tending to grab. Curve A of figure 8 is a plot of the peak values of the beginning spikes as taken from the 30 monitored tests of the 500-hole series in steel. After about 80 holes, these beginning spikes show a decrease in amplitude (with a good deal of scatter), until after about 400 holes the response tends to flatten at an amplitude of about 70 percent of the initial values. Curve B of figure 8 is a plot of the torque amplitudes in the "plateau" region; the amplitudes are relatively constant. Amplitude values of the terminal, or breakthrough, spike are not plotted as they were too large to be recorded with the oscilloscope vertical deflection required for other traces.

The bottom trace of photograph A of figure 6 represents drill-bit displacement. The initial part of the curve corresponds to the lowering of the drill bit by the slow-speed motor. As noted, the drill bit must be lowered faster than the drill cutting rate but not so fast as to shock excite the load cell. Toward the end of the drilling process, as anticipated, the displacement rate increases rapidly as the drill approaches breakthrough.

The time required to drill through a 1.3-cm thick steel workpiece with a 1-cm diameter drill increased from about 11.5 s to about 13.5 s by the 200th consecutive hole; then the drilling time began to decrease so that by the 500th hole it was down to 12.5 s. The data for the 30 monitored holes are represented by curve C of figure 8.

This discussion of the results has been concerned with quasi-static measurements of load, torque, and drilling time. The analysis of dynamic data is exemplified by figures 9 and 10, which together show a set of eight photographs of traces on the oscilloscope screen taken during the drilling of holes 60 and 61 in steel. Photograph B of figure 9 shows the a-c ripple on the load signal (top trace) and the torque signal (bottom trace) after passing through a 16-Hz low-pass filter (sweep time 50 ms/div); a signal at the 12-rps spindle rotation frequency can clearly be seen. For the traces of photograph C of figure 9 the same signals are passed through a 32-Hz low-pass filter; earlier tests had indicated that a signal at 24 Hz, or the "two-flute frequency," would be detected. In those tests, however, there was little evidence of a 24-Hz signal. Photograph D of figure 9 shows a sample spectral frequency analysis covering the frequency range 0 to 200 Hz of the load signal (unfiltered except for transient recorder response) in which the contributions of the spindle frequency of 12 rps and the drill-press table resonance frequency of 117 Hz can be seen. Curves A and B of figure 11 show the analyzed amplitudes at these two frequencies as a function of the number of holes drilled. The amplitude of the 12-Hz component rises sharply until about 80 holes have been drilled; beyond 80, the amplitude levels off for the remainder of the test. The amplitude of the 117-Hz component appears virtually unchanged during the entire 500-hole test, with possibly a slight rise in amplitude as a function of the number of holes drilled. Photograph E of

figure 9 shows a sample spectral frequency analysis of the torque signal; again, components are evident at the drill-spindle frequency and the drill-press table resonance frequency. In this example, the component at the spindle frequency is much more pronounced than that at the table resonance frequency. Curve C of figure 11 shows the data plotted for the entire test, and shows little or no evidence of change. Photographs B and C of figure 10 show a sample spectral frequency analysis over the range 0 to 2000 Hz for the load and torque signals, respectively. The most pronounced component is in the torque signal at 750 Hz. The amplitude of this component is shown plotted as curve D of figure 11; again, very little change in amplitude can be detected, although there is considerable scatter in the data.

None of the four plots of frequency-analysis data in figure 11 show any significant changes in amplitude during the entire series of 500 holes.

An earlier test series of 500 holes in brass preceded the series in steel. The test series in brass showed so little change that a new series was begun with steel; because changes from the first to the last hole do not appear to be significant, only a few trace photographs are presented for the test in brass. Figure 7 shows photographs of the displacement, load, and torque traces for hole numbers 1, 100, 200, 300, 400, and 500. The drilling time increased with number of holes drilled from about 3.5 to 4 s.

2.3.3 Use of Instrumentation Tape Recorder - After the two 500-hole drilling experiments had been completed, an instrumentation tape recorder that had been ordered by the sponsoring office was made available for a brief evaluation. Several test runs were carried out in which the data from drilling a hole were recorded continuously from first engagement to breakthrough (instead of only 500 ms, 50 ms, or 10 ms) by means of a tape-loop accessory. The tape was played back into the spectrum analyzer repetitively. Time constraints interrupted these experiments before definitive conclusions could be drawn. On the basis of the limited tests, use of the recorder would be expected to improve the frequency-analysis capability significantly for future drilling experiments.

3. DISCUSSION AND CONCLUSIONS

The principal aims of the work — to develop apparatus for measuring the down force (load) and torque imparted to the workpiece by a drill bit in a drill press during drilling and to gain some familiarity with the practical problems of instrumenting a machine tool — have been achieved. This exploratory program of work was not primarily intended to provide information on the behavior of the measured parameters; the 500-hole limit and the use of a single bit in steel was determined by managerial considerations of available time and personnel.

However, it may be of interest to examine the trends of the recorded parameters keeping in mind the constant-rpm, constant-load mode of operation. A descriptive explanation of cutting-tool wear is that a sharp, microscopically jagged edge becomes burnished with use as a result of microimpacts between the workpiece and locally high points on the edge and as a result of complex mechanisms involving microstructural changes, plastic deformation and flow, and other aspects of the behavior of material subjected to mechanical and thermal stress. This description is confirmed by the common shop experience that a dull bit or cutter requires an excessively high feeding force to thrust the tool into the work; if the tool cuts at all, the operation time is greatly increased compared to the normal time required with a reasonably sharp tool, and there is usually evidence of considerable heating of the tool and workpiece. In a constant-load mode of operation, as the tool wears and becomes smoother, the torque required to turn it would be expected to decrease. For drilling in a constant-rpm, constant-load mode, if the torque required to turn the drill decreases, the implication is that there should be less material removed per revolution of the bit, and the drilling time for a given thickness and composition of workpiece should accordingly increase. These predictions are confirmed in curves B and C of figure 8, up to about hole 300. After hole 300, the trends for both curves reverse. The net change in both parameters is on the order of 10 percent. Visual examination of the drill bit shows that the cutting end has experienced temperatures high enough to cause permanent discoloration of the steel, with dark blue-black at the tip and along the cutting edges and with gradations from this coloration to pale straw some 3 cm from the tip. Examination of the cutting edges with a zoom microscope in the nominal magnification range 70 to 180X shows the presence of both burnished areas decorated with small modules of apparently fused material and freshly scored areas with parallel ridges similar in microtopography to the ground surfaces of a new bit. A possible explanation of these observations and of the reverse trends in the torque and drilling-time curves may be that near hole 300 the condition of the drill resulted in the unlubricated bit reaching successively higher temperatures with each successive drilling until flakes of material were being removed at localized sites. It is suggested that the effect of this process was to produce sites with cutting properties at least in some respects similar to those of a new bit and that the number of such sites increased as the number of holes drilled increased beyond 300.

Three prominent frequencies appear in the frequency analysis data, these being (1) the drill spindle speed of 12 Hz, (2) the drill-press table resonance of 117 Hz, and (3) from an unknown source, 750 Hz. There appears to be little correlation between the number of holes drilled (and, presumably, drill wear) and the amplitude of any of these frequencies.

4. RECOMMENDATIONS

4.1 Overall Considerations and Principal Recommendation

A major conclusion drawn from reviewing the references in the associated bibliography on machine-tool measurements [2] is that "calibration

needs have not been broadly addressed;" further, "there is a real danger that calibration methods will not be available to match the technology." This conclusion identifies an important element of a long-term National Bureau of Standards program in machine-tool automation which is responsive to the Visiting Committee's recommendations. It identifies also a legitimate role for the Components and Applications Section in the machine-tool automation field. The Section has had long experience with the measurement of pressure, vibration, and the like, and with the development of both static and dynamic methods for calibrating such measurements. Thus, the development of calibration methods for machine-tool sensing falls appropriately within an area of technical expertise on the part of the Section staff and within the intended scope of Section activity.

The principal recommendation of this report is that resources be allocated to the Section in support of the exploratory and engineering development required to realize calibration methods for machine-tool sensing.

4.2 Specific Recommendations for Immediate Work

The work reported represents the first step in a logical program of effort aimed at developing calibration methods for machine-tool sensing. Continuing effort will be required to obtain sufficient data for a meaningful evaluation of drill-press and other machine-tool performance to provide, in turn, a basis for assessing those calibration requirements that arise from the measurement situation as opposed to external constraints. Specifically, it is recommended that:

1. The drilling experiments be extended both in number of drill bits used and in number of holes drilled. Data should be taken more frequently and the series extended until an increase in drilling time on the order of 100 percent is achieved. The tape recorder with loop attachment should be incorporated into the instrumentation chain to permit frequency analysis of the data from drilling an entire hole (or at least to provide a means of checking that data taken over a small fraction of the drilling time are representative of data from the entire hole, with the possible exception of touch-down and breakthrough times). Analysis of the data should be correlated with microscopic examination of bits at selected intervals in the series.

2. Efforts continue toward the realization of a more compact, convenient test fixture suitable for use in the machine shop. The performance of this test fixture should be compared to that of a fixture known to be commercially available and incorporating piezoelectric quartz-crystal sensing elements for multi-axis measurements.

3. Experiments be conducted using a drill press operating in a constant spindle-feed mode to permit comparison between the rate of drill-bit wear in the constant-load and constant-feed modes.

4. A continuing search of the literature, coupled with liaison between other NBS organizations conducting work in machine-tool automation, be maintained as an essential part of this effort.

4.3 Recommendations for Further Work

1. It is recommended that, using the background developed in the earlier investigations, a survey of machine-tool calibration needs be carried out with the goal of identifying important parameters, such as dynamic force, for which there is little or no calibration support available and that appropriate work be undertaken to respond to the needs after priorities are assigned.

2. It is recommended that calibration methods for the selected measurand be developed, first in terms of laboratory procedures and subsequently as methods suitable for in-shop use, such methods to be documented and disseminated.

3. It is recommended that additional measurands be selected as subjects for supporting calibration and that development of methods proceed as before. At this stage it should be possible to develop field calibration procedures for the sensors incorporated in the fixtures discussed in (2) of 4.2 above.

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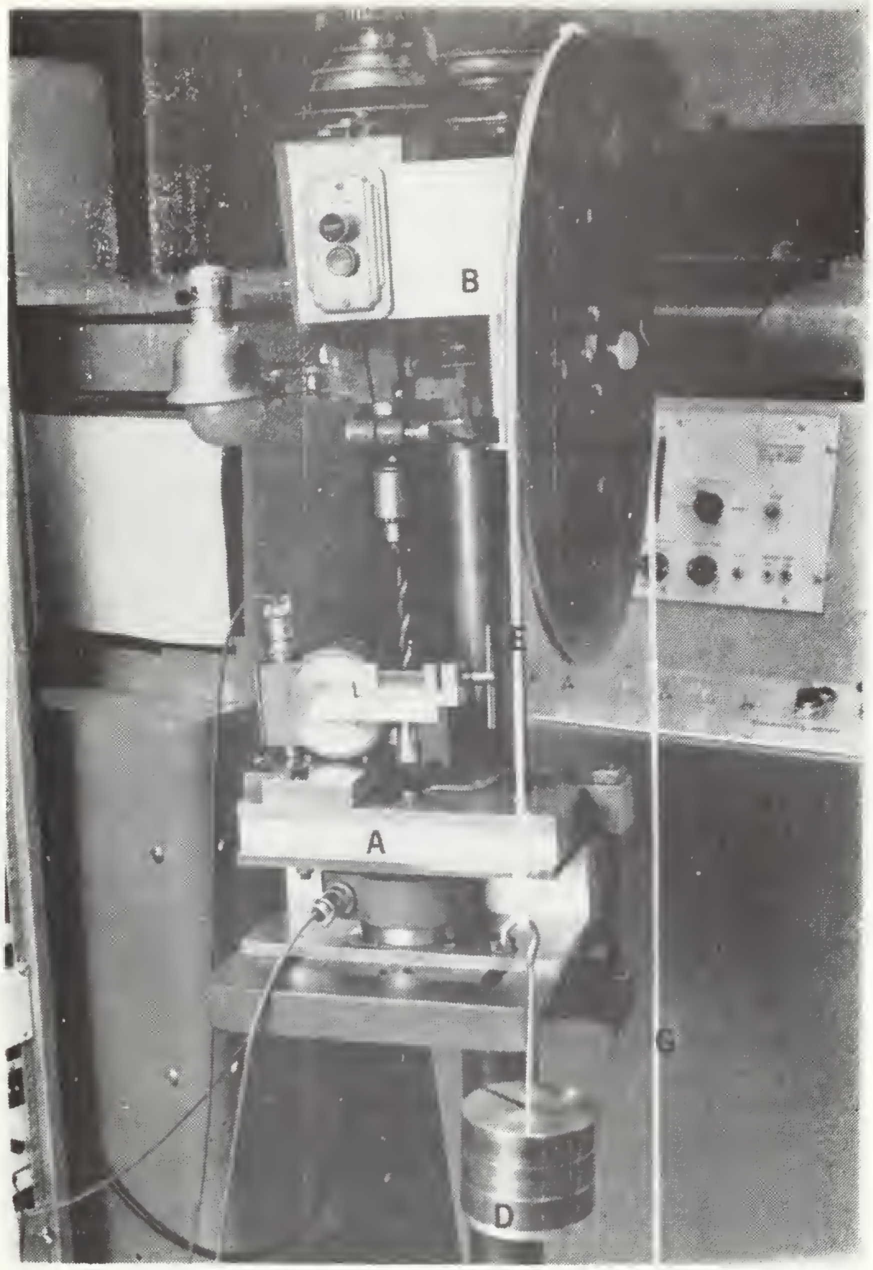

Figure 1: Drill press with instrumentation. Identified are the load-and-torque measuring fixture - second model (A); the linear-variable-differential transfomer (LVDT) displacement transducer (B); and the spindle-speed sensor (C). Also shown is the means by which a load is applied to the spindle. Masses on pan (D) exert a force on the drive rope (E), which is fastened in the groove of large pulley (F). Pulley F thus experiences a torque which is in turn transmitted to the spindle pinion to which the pulley is rigidly attached. Rope (G) leads to a low-speed geared motor, as described in the text.

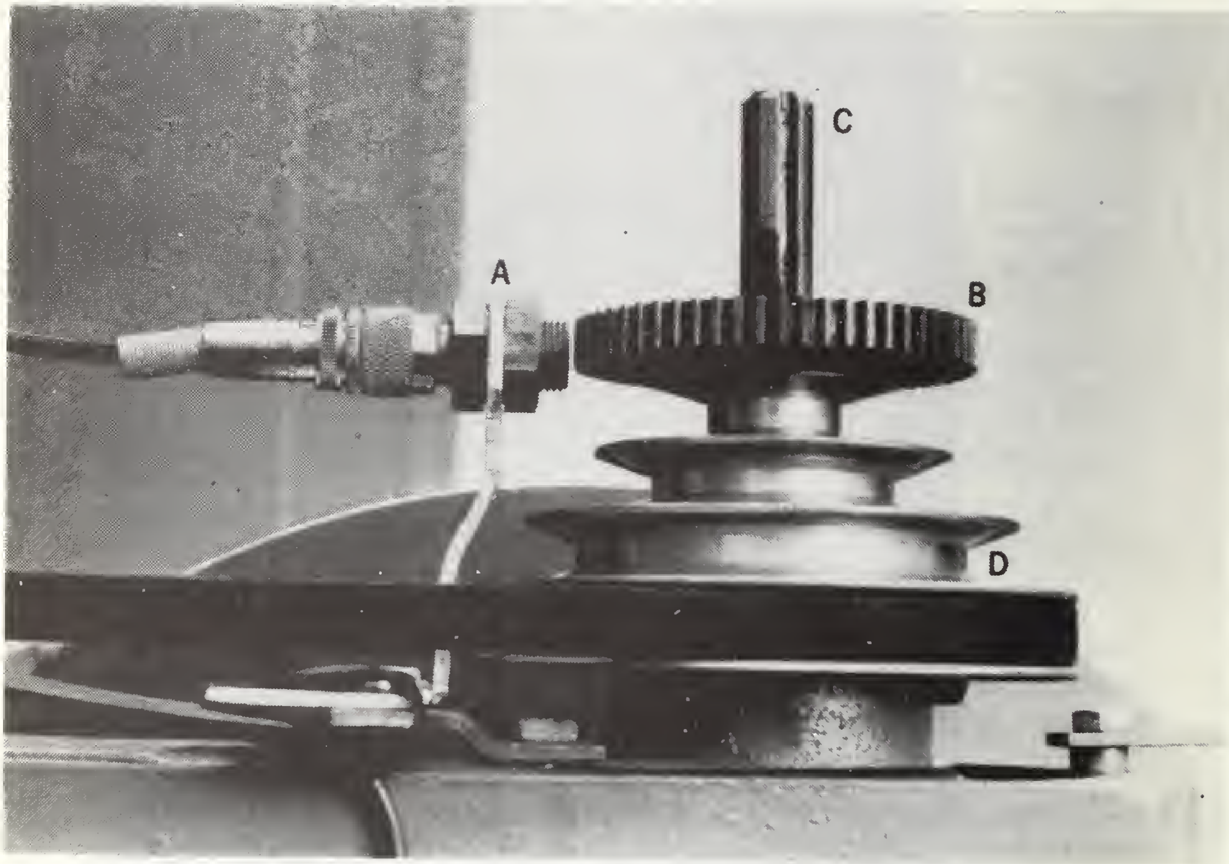

Figure 2: Drill spindle-speed instrumentation. Identified are the magnetic sensing coil (A) and the 60-tooth steel gear (B) mounted on the spindle shaft (C). One of the two stepped pulleys of the belt drive is shown at (D).

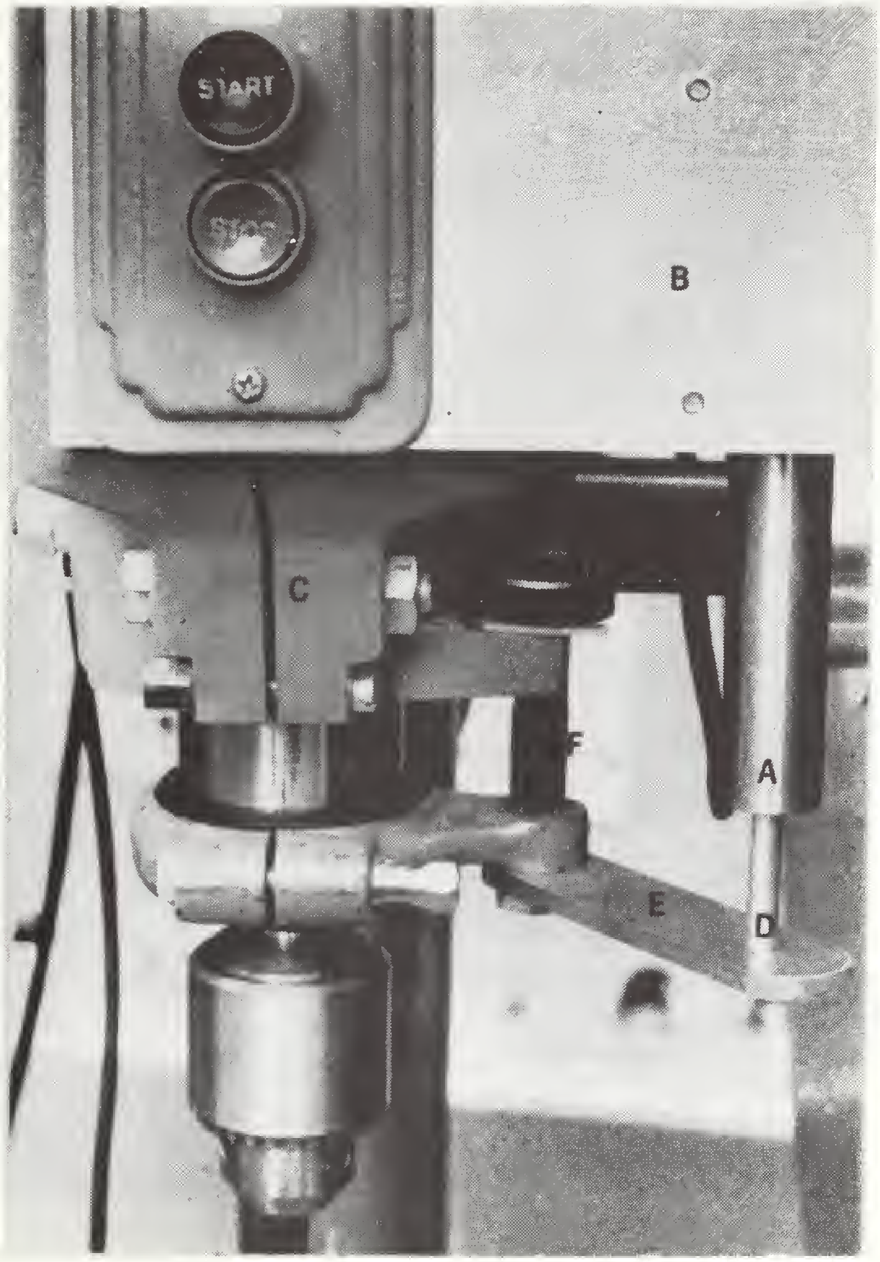

Figure 3: Displacement-measuring instrumentation. Identified are the LVDT transducer sensing coil (A) mounted by means of bracket (B) to the head casting (C). The transducer armature (D) is mounted by a bracket (E) attached to the vertical stop screw (F).

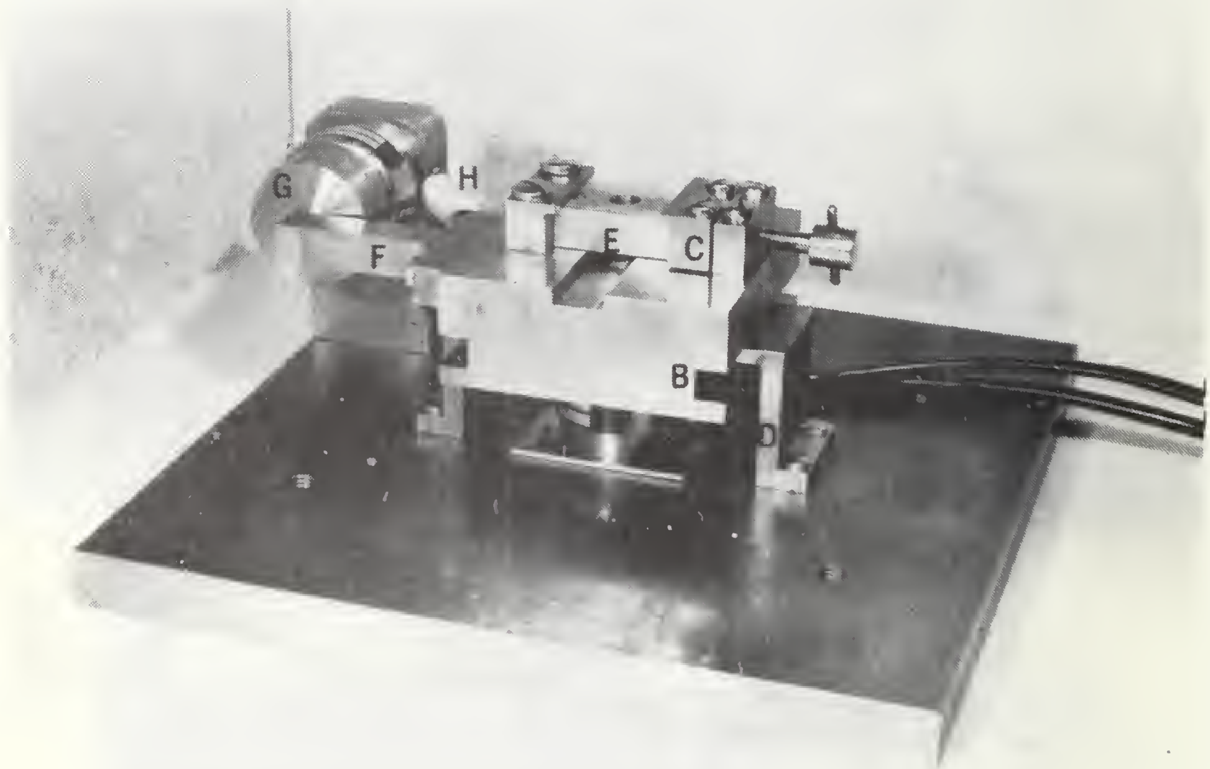

Figure 4: Force-and-torque measuring fixture - first model. Identified are the mounting plate (A) carrying the load-measuring load cell: the machined block (B) bearing on the capped armature of the load cell and carrying vise jaws (C): and the brackets (D) that restrain lateral motion of the block and hence of the workpiece (E). Also shown is the arm (F) extending from the block to contact the armature of the torque-measuring load cell (G). The spring (H) applies a preload to the cell so that the arm does not bounce against the armature.

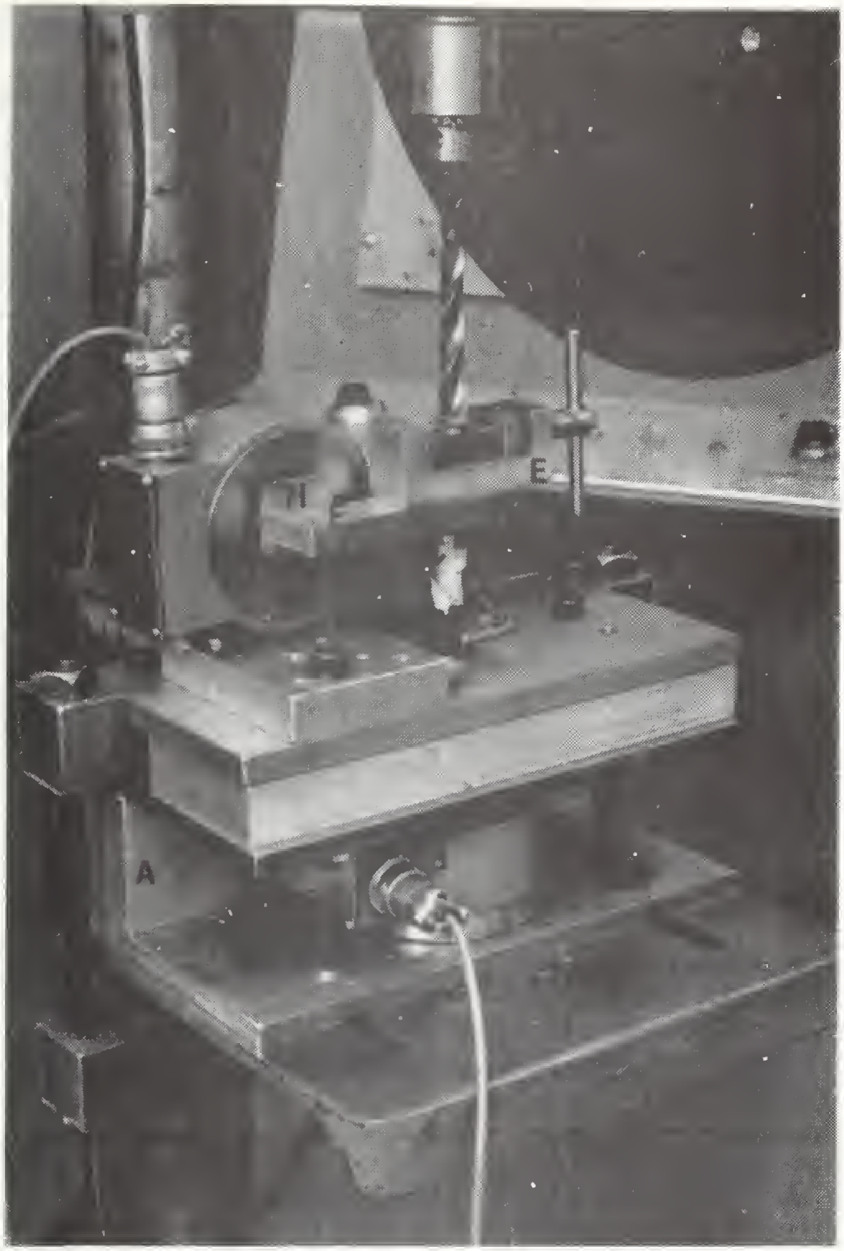

Figure 5: Force-and-torque measuring fixture - second model. Identified are the length of U-channel (A) into which the load cell (B) measuring downward force is mounted: the brass rod (C) instrumented with strain gage (D) and supporting vise (E) with arm (F). Also shown are the load cell (G) measuring torque and shims (H) for adjusting torque preload. The workpiece is in the vise at (I).

A B C D E F

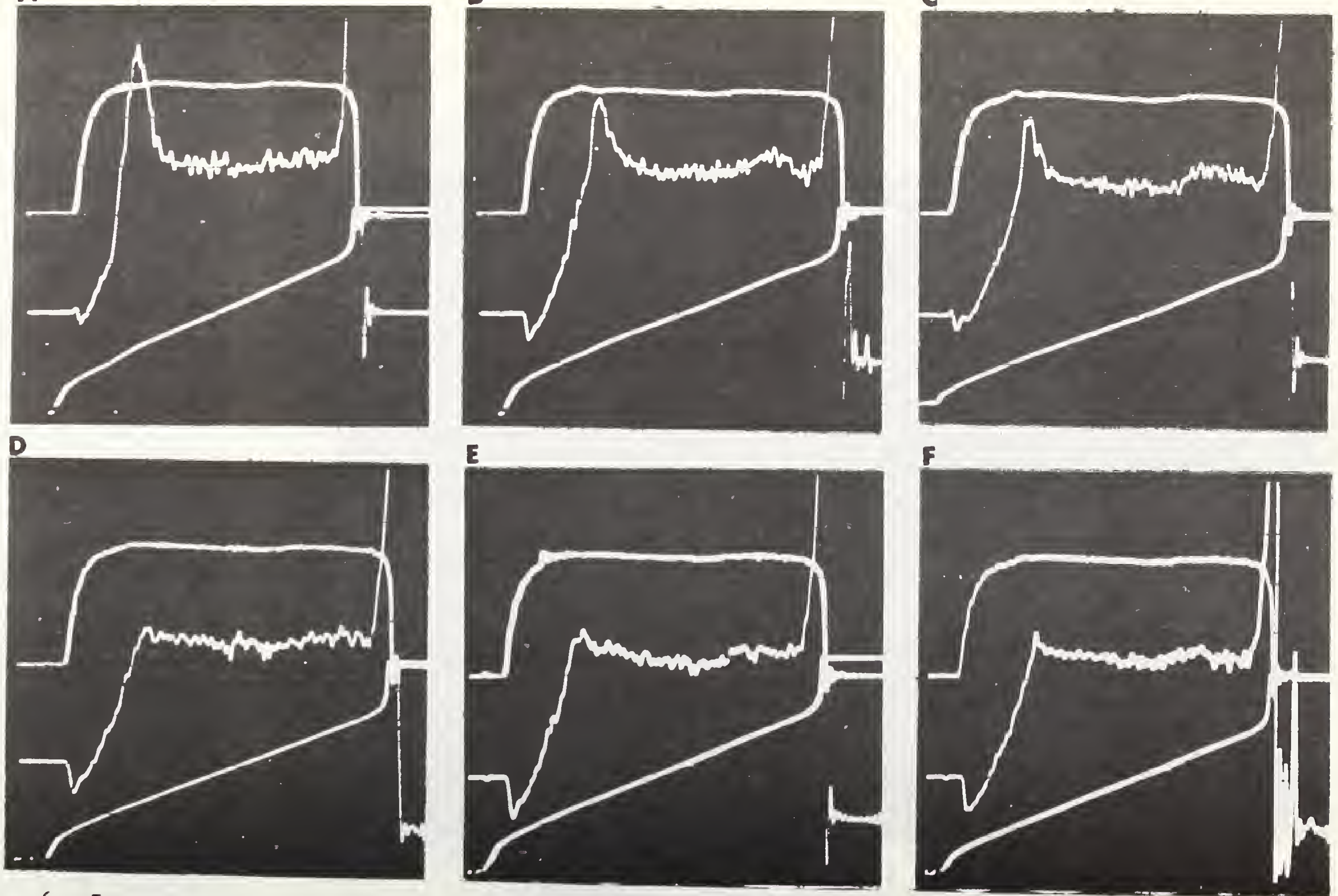

Figure 6: Force, torque, and displacement instrumentation signals as a 1-cm-diameter hole is drilled in 1.3-cm-thick steel. Top trace each photograph: force load-cell output signal, through a 5-Hz low-pass filter. Middle trace each photograph: torque output signal, through a 5-Hz low-pass filter. Bottom trace each photograph: displacement transducer output signal. Time base is 2 s/div. Photographs A, B, C, D, E, and F represent data from drilled holes number 1, 100, 200, 300, 400, and 500 respectively.

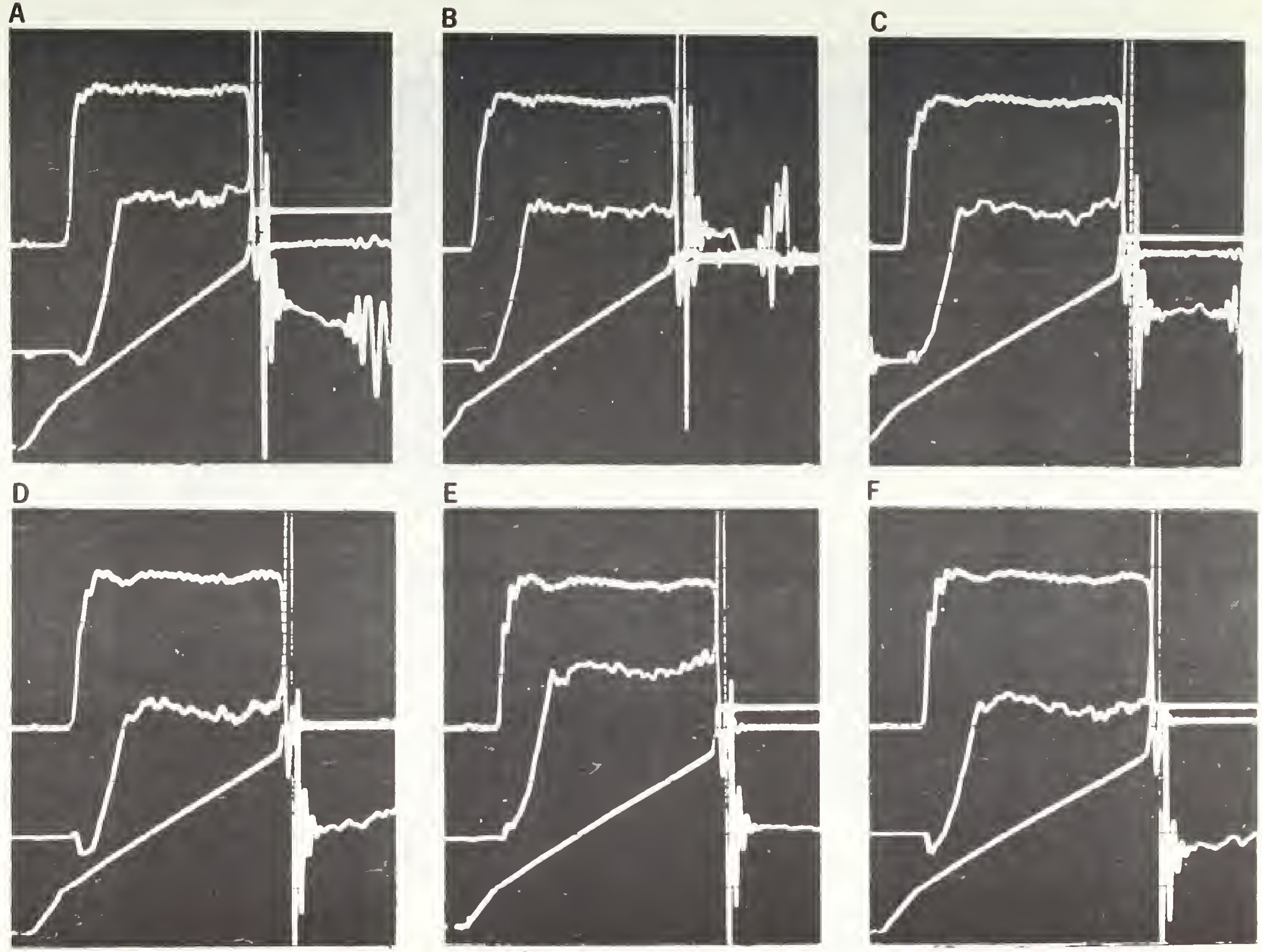

Figure 7: Force, torque, and displacement instrumentation signals as a 1-cm-diameter hole is drilled in 1.3-cm-thick brass. Top trace each photograph: force load-cell output signal, through a 5-Hz low-pass filter. Middle trace each photograph: torque output signal, through a 5-Hz low-pass filter. Bottom trace each photograph: displacement transducer output signal. Time base is 2 s/div. Photographs A, B, C, D, E, and F represent data from drilled holes number 1, 100, 200, 300, 400, and 500 respectively.

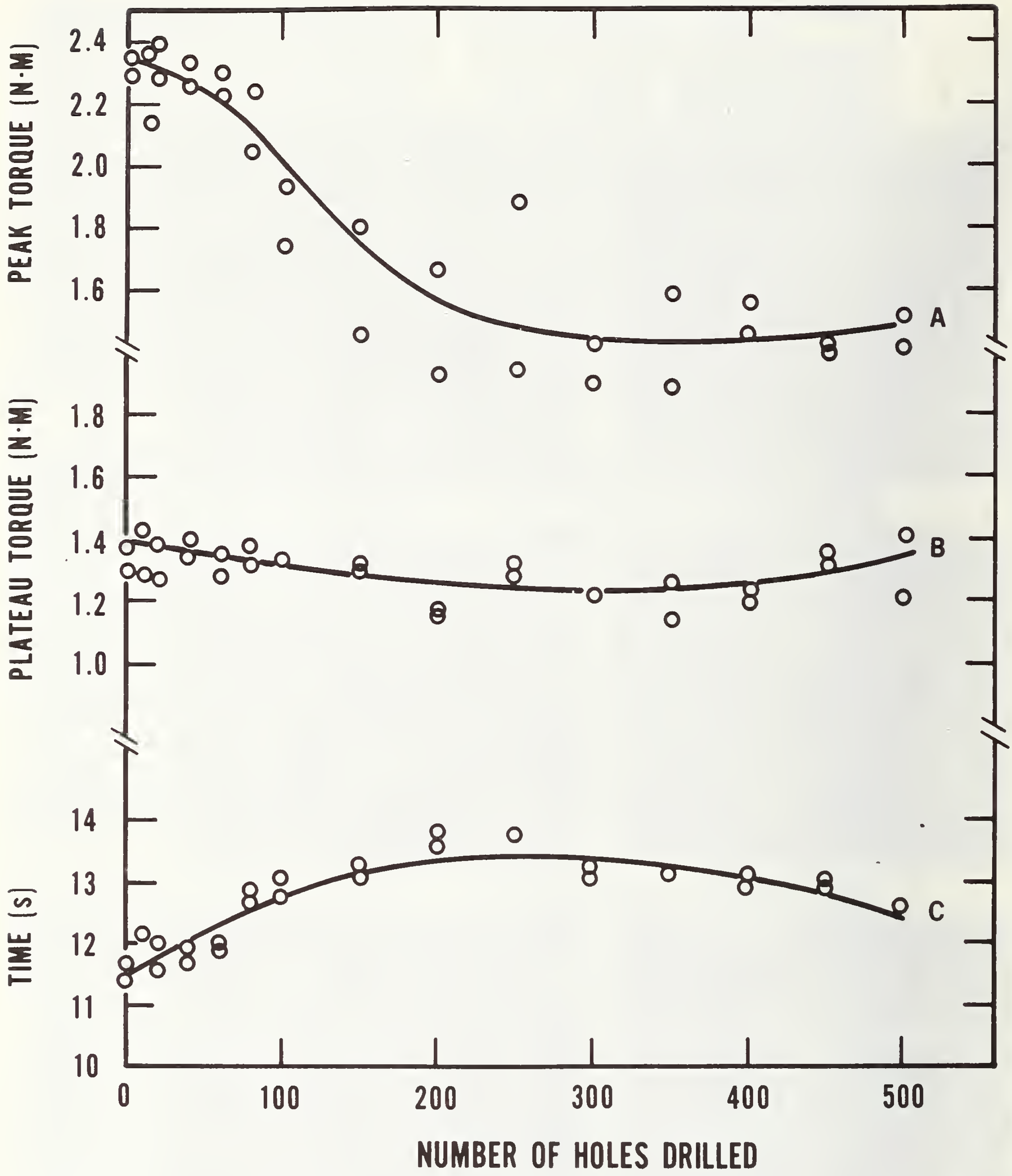

Figure 8: Drilling time and torque signal as a function of number of holes drilled in steel.

A - Output signal of the torque load cell (measured at the peak of the first torque spike).
B - Output signal of the torque load cell (measured in the plateau region).
C - Time to drill through a 113-cm thick piece of steel with a 1-cm drill.

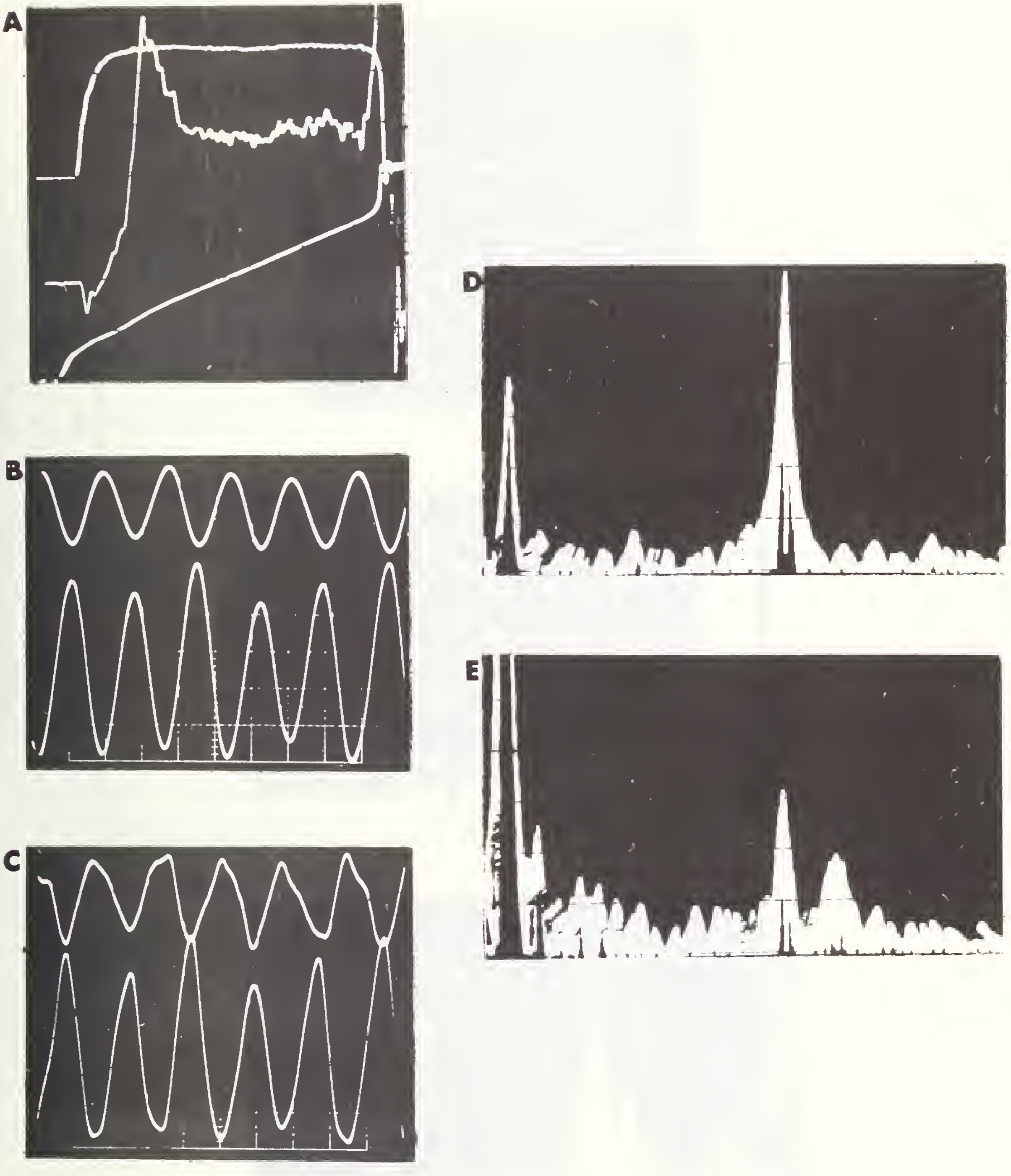

Figure 9: Typical output waveforms and frequency analysis of force and torque instrumentation signals. Five oscilloscope photographs for the 60th hole drilled in steel are shown (figure 10 shows the remaining three oscilloscope photographs for the 61st hole). Two drillings and eight photographs represent a set of data.

A - See figure 6 for details.
B - Top trace, force load-cell output signal through a 16-Hz low-pass filter, horizontal scale 50 ms/div; bottom trace, torque load cell output signal through a 16-Hz low-pass filter, horizontal scale 50 ms/div.
C - Same as B, except through a 32-Hz low-pass filter.
D - Frequency analysis of force load-cell output signal; horizontal scale 20 Hz/div, vertical scale 10 mV/div.
E - Frequency analysis of torque load-cell output signal; 100 Hz center, frequency, horizontal scale 20 Hz/div, vertical scale 50 mV/div.

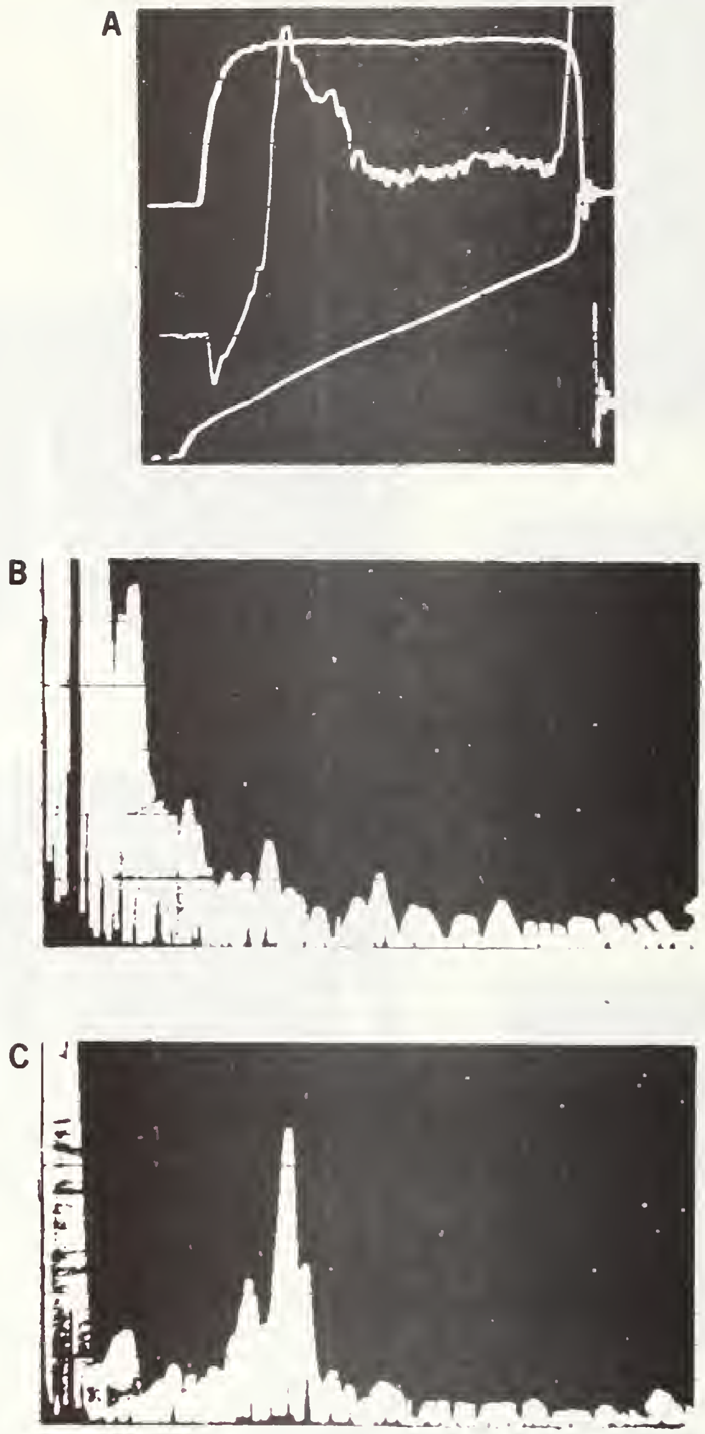

Figure 10: Typical frequency spectra to 2 kHz of force and torque instrumentation signals. Figure 10 shows three oscilloscope photographs for the 61st hole drilled in steel; the other five photographs that make up this set are shown in figure 9.

A - See figure 6 for details.
B - Frequency analysis of force load-cell output signal; horizontal scale 200 Hz/div, vertical scale 2 mV/ div.
C - Frequency analysis of torque load-cell output signal; horizontal scale 200 Hz/div, vertical scale 20 mV/div.

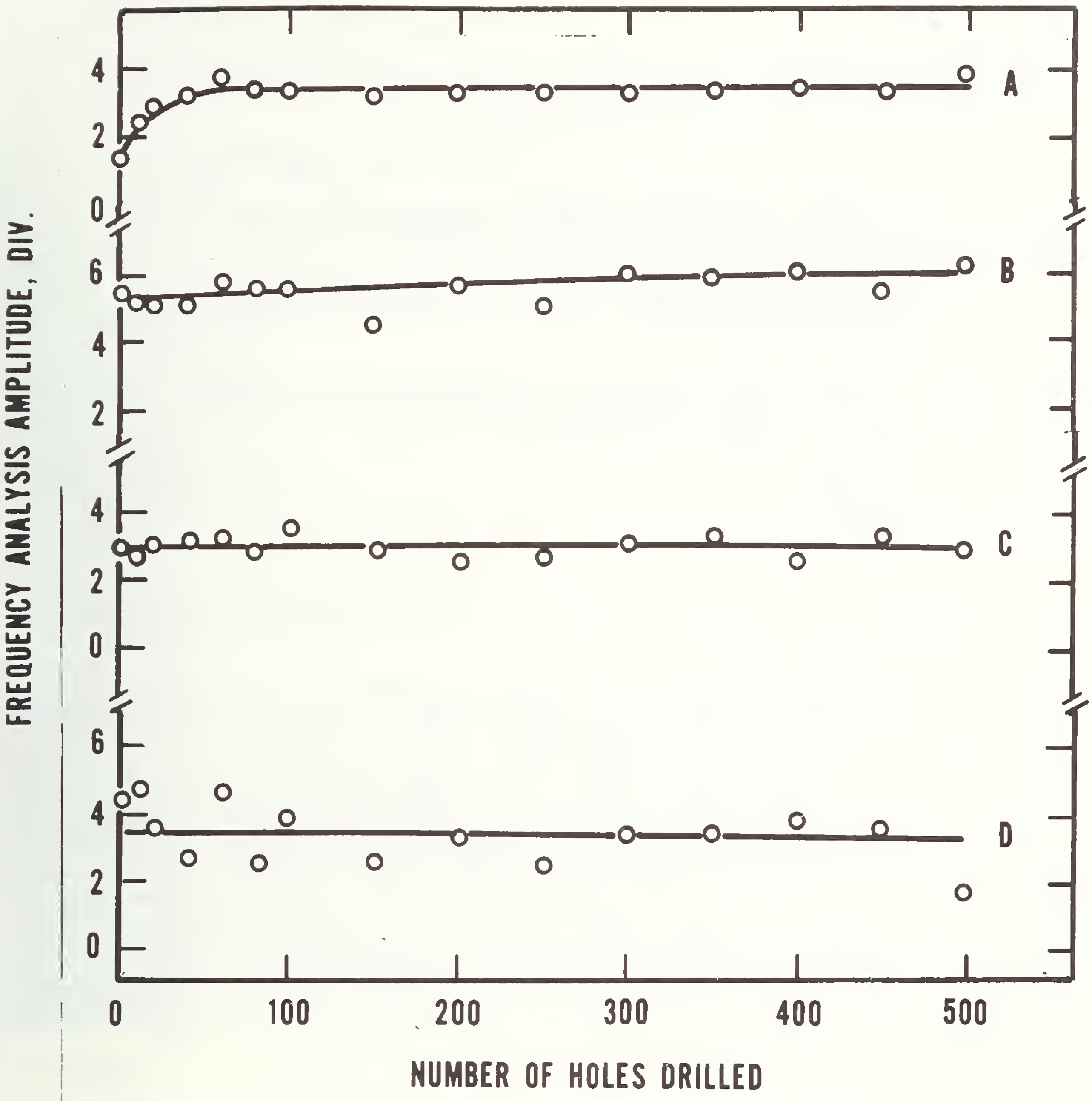

Figure 11: Plots of spectral amplitude at selected frequencies as a function of number of holes drilled. Data for both force and torque are shown. The amplitude data are scaled from the four frequency-analysis oscilloscope photographs taken for each set of holes drilled in steel. (Typical oscilloscope photographs are shown in figures 9 and 10.)

A - Response for 12 Hz (drill spindle frequency), force load-cell output signal.
B - Response for 117 Hz (drill-press table resonance frequency), force load-cell output signal.
C - Response for 117 Hz (drill-press table resonance frequency), torque load-cell output signal.
D - 750 Hz,(source unknown), torque load-cell output signal.

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16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

The development of an experimental instrumentation system for a small drill press is described. The parameters measured are spindle speed, vertical spindle displacement, vertical spindle load, drilling torque, and drilling time. Several test fixtures were instrumented and used in drilling experiments. These experiments were conducted to examine the relationship between variations in the measured parameters and drill performance, more specifically to drill wear. Experimental data show a 10-percent increase in drilling time from the first hole to the last for a single set of 500 holes drilled in cold-rolled steel at a nominally constant load, although the drilling time began to decrease slightly after hole 300. Changes in drilling torque were also detected during the test runs, and in similar runs with a brass workpiece. It is suggested that with respect to the anomalous results in steel under the unlubricated, constant-force conditions employed, the cutting surfaces of the drill bit were in a sense being renewed as microflakes of material departed to reveal fresh, sharp unburnished sites.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Cutting force; drill bit; drill press; dynamic; force; load; machine tool; measurement; on-line; tool wear; torque; transducer.

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